Chapter-6

Computational Tools for Light Scattering Studies of Irregularly Shaped Particles

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This chapter gives a general idea about light scattering computations of nonspherical and irregularly shaped small particles and its importance in the study of realistic particle systems (for eg. atmospheric aerosols, interstellar dust, nano particles). This chapter briefly explains the different computational techniques (DDA, T-Matrix) etc. used in the characterization of irregular and complex geometric shapes and their applicability in light scattering studies.

1. INTRODUCTION TO LIGHT SCATTERING BY NONSPHERICAL PARTICLES

The light scattering studies of irregularly shaped particles presents a challenge for characterization of their optical properties. Scattering of light

by small particulate matter is a very important tool in climatology, remote sensing, astrophysics, and study of atmospheric aerosols etc. The scattering of light by spherical particles can be computed easily by the conventional Lorenz–Mie theory or its modifications [1]. Mie theory can also be used in study of nonspherical particles. But the sphericity assumption will never lead to accurate results, because the scattering properties of irregular particles differ significantly from those of volume equivalent spheres.

Some beautiful and significant optical phenomena are results of light scattering by nonspherical particles such as halos, arcs, pillars and lidar backscatter observed for ice crystals [2] and Interstellar polarization caused by dust grains etc. [3]. But it's difficult to compute the radiation and scattering properties of highly irregular and complex particles using conventional theories. Some examples of such particles are atmospheric aerosols, soot particles, interstellar and cosmic dust particles, dust grains present in the cometary tail, snow and frost crystals, ocean hydrosols, and biological microorganisms(for eg. diatom). It also has its applications in optical communications engineering, and photonics technology. Specifically, in near-field or nano-optics and the design of optical sensor, biosensors or particle surface scanners. The light scattering and radiative properties of nonspherical and highly irregular particles can differ dramatically from those of "equivalent" Mie spheres. Therefore the light scattering by irregularly shaped particles should be accurately computed and measured in order to understand the effects of particle nonsphericity on scattering patterns and other radiative properties [4].

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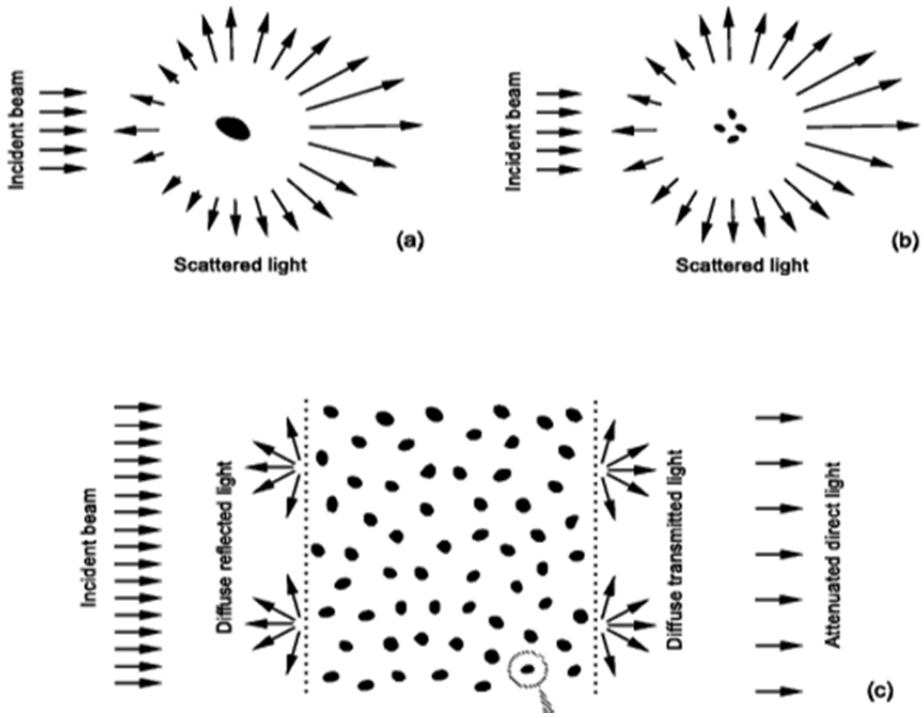

Fig. 1: (a) Far –field scattering by a single particle, (b) Far field scattering (c) Multiple scattering, by a system of randomly oriented particles (Figure source: Mishchenko et al.[30]).

The development of different refined computational tools and advanced numerical algorithms has led to detailed understanding of the scattering properties of nonspherical, non homogeneous and anisotropic particles at visible as well as infrared and ultraviolet wavelengths. Particles encountered in realistic environments are not always spherical, they are nonspherical, nonrotational, symmetric, inhomogeneous, coated, chiral or anisotropic [5]. The scattering properties of nonspherical particles can be computed theoretically and measured experimentally, but both approaches

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have their strengths and weaknesses. Theoretical modeling allows to run all the physical parameters used in the computation to run as variables for eg. size, shape, refractive index, orientation etc. by simple modification of the original code. But modeling of complex particle systems is a very tough and expensive work requiring high degrees of computing power and resources and still unable to simulate with accuracy the scattering properties of natural particles. Experimental measurements using visible or infrared wavelengths can study real particle samples, either natural or artificial. But these experiments need expensive instruments, and are unable to measure all the scattering parameters accurately at the same time. The only way to precise determine the optical properties of realistic sample is a combination of efficient theoretical and experimental approaches [6].

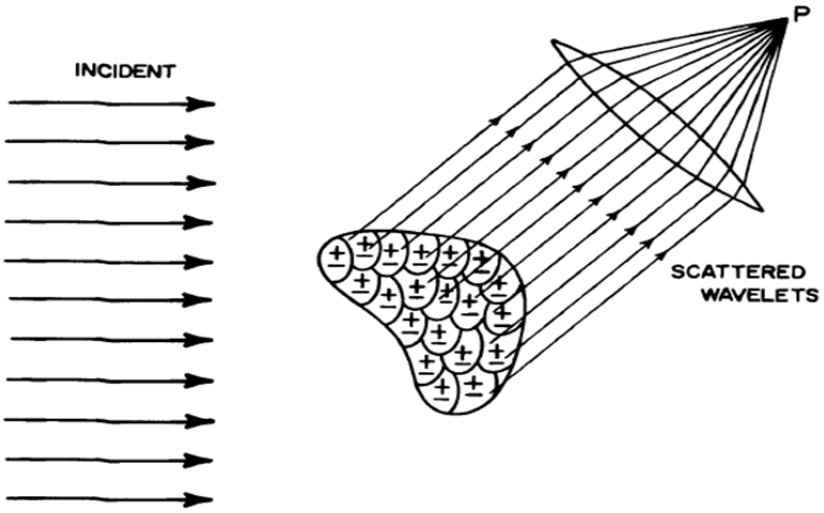

Fig. 2: The total scattered field at P is the resultant of all the wavelets scattered by the regions into which the particle is subdivided (Figure source: Bohren & Huffman, [1]).

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2. THEORY OF LIGHT SCATTERING

2.1. The Parameters required for characterization of particulate matter

The most important parameter is particle characterization is the size parameter. It is defined as: $x = 2\pi r/\lambda$, where *r* is the particle size (radius of the target particle or volume-equivalent sphere) and λ is the wavelength of light in the scattering medium. The second most important parameter is the aspect ratio of the target particle, which is defined as the ratio of maximum to minimum particle dimensions. The third parameter is the refractive index (n) of the scatterer. The efficiency of a numerical technique is characterized by its computational complexity, that is, the dependence of the number of computer operations on the size parameter of the particle [5, 6].

All light scattering theories and numerical techniques for computing the scattered electromagnetic field are based on solving Maxwell's equations, which is referred to as the scattering problem. The exact analytical solution is reduced to solving the vector Helmholtz equation for the time-harmonic electric field using the separation of variables technique. The incident electric field and the field inside the scatterer are expanded into regular eigenfunctions and the scattered field outside the scatterer is expanded in eigenfunctions that reduce to outgoing waves at infinity. Subjecting the resulting equations to boundary conditions the unknown expansion coefficients of the internal and scattered fields are determined from the known expansion coefficients of the incident field [7, 8].

The numerical techniques for computing electromagnetic scattering by nonspherical particles can be categorized as Differential equation methods

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which compute the scattered field by solving the vector wave equation in the frequency and time domains, and the integral equation methods are based on the volume or surface integral counterparts of Maxwell's equations. Most of the theoretical techniques compute the scattered electric field for a single particle in a fixed orientation, whereas practical applications often require knowledge of ensemble-averaging of parameters such as optical cross sections and scattering matrix elements.

2.2. The scattering matrix:

The scattering properties of a finite target can be fully described by the Stokes parameters (I_i, Q_i, U_i, V_i) for incident wave and (I_S, Q_S, U_S, V_S) for the scattered wave.

These parameters are related by the 4×4 Mueller Matrix as follows [9, 10]:

$$\begin{pmatrix} I_S \\ Q_S \\ U_S \\ V_S \end{pmatrix} = \frac{1}{k^2 d^2} \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix} \quad \ldots\ldots\ldots (1)$$

Where 'S' represents the Mueller matrix elements. I_s, Q_s, U_s and Vs are stokes parameter of the scattered light. I_i, Q_i, U_i and V_i are the corresponding parameters of incident light. The subscripts *i* and *s* refer to the incident and scattered beams, *k* is the wave vector and *r* is the distance from the sample to the detector.

To simplify the computations of light scattering process only single scattering is mostly considered for randomly distributed particle systems. This means that particles are separated widely enough, so that each particle

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scatters light in a particular direction irrespective of the presence of other particles in its vicinity and the resultant scattered field is a vector summation of light scattered by all the individual particles present in the scattering system. Due to lack of systematic phase relations between partial electromagnetic waves scattered by different particles the individual scattered intensities of the partial waves can be added without giving significant importance to phase.

2.3. Randomly Oriented systems

In the following analysis we consider scattering by an ensemble of randomly oriented, identical particles. Random particle orientation means that the orientation distribution of the particles is uniform. As a consequence of random particle orientation, the scattering medium is macroscopically isotropic, i.e., the scattering characteristics are independent of the incident and scattering directions e_k and e_r, and depend only on the angle between the unit vectors. It is convenient to direct the *Z*-axis along the incident direction and to choose the *XZ*-plane as the scattering plane.

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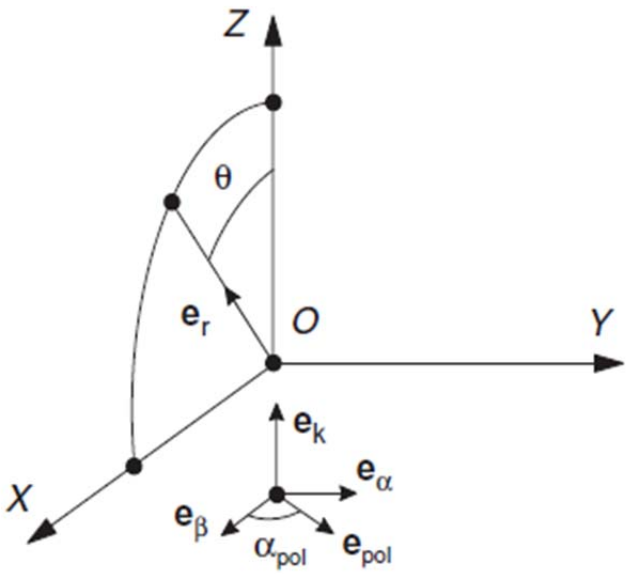

Fig. 3: A typical scattering system for randomly oriented particles (Figure source: Doicu. A.,[6]).

The assumption of independent or single scattering greatly simplifies the problem of computing multiple light scattering by a collection of particles [11, 12]. However in the realistic scenario for a collections of randomly positioned particles or widely separated particle aggregate systems, scattering in the forward direction is always coherent and causes attenuation of the incident wave as it propagates through the medium [1, 9]. Also particles present in clusters or aggregates in close proximity to each other, affects the fields scattered by all other particles in the system making the computations more complex and rigorous.

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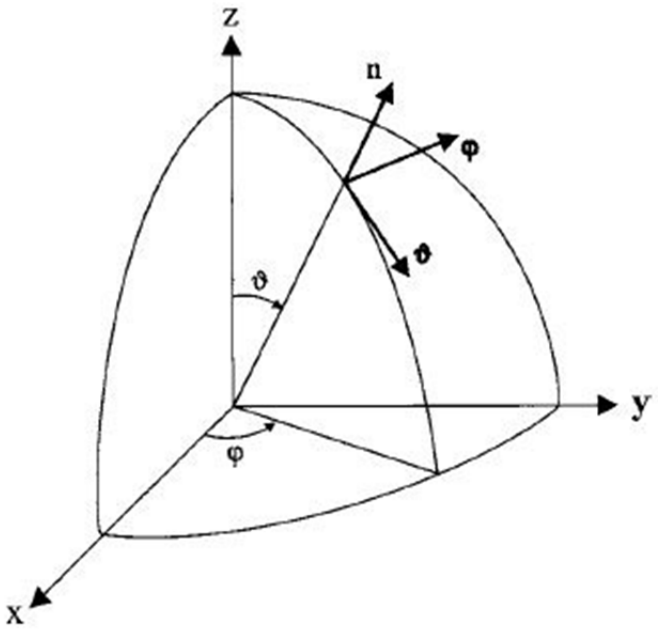

Fig. 4: Scattering plane of an electromagnetic wave (Figure source: Mishchenko et al., [5]).

To describe the scattering of a plane electromagnetic wave by a nonspherical particle in an arbitrary orientation, we must first specify the directions of the incident and scattered waves and the orientation of the particle with respect to a reference frame. Let this reference frame be a right-handed Cartesian coordinate system L (Laboratory reference frame) with orientation fixed in space, having its origin inside the particle. The direction of propagation of a transverse electromagnetic wave is specified by a unit vector **n** or, equivalently, by a couple (θ,ϕ) $\theta \in [0,\pi]$ is the polar (zenith) angle measured from the positive z axis, and $\phi = [0,2\pi]$ is the

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azimuth angle measured from the positive x axis in the clockwise direction, looking in the direction of the positive z axis [5].

3. RADIATIVE TRANSFER EQUATION FOR RANDOMLY ORIENTED SYSTEM

The general radiative transfer equation for a nonemitting medium comprising sparsely and randomly distributed, spherical or arbitrarily oriented nonspherical particles is as follows [12]:

$$\frac{d\mathbf{I}(\mathbf{n})}{ds} = -n_0 \langle \mathbf{K}(\mathbf{n}) \rangle \mathbf{I}(\mathbf{n}) + n_0 \oint_{4\pi} d\mathbf{n}' \langle \mathbf{Z}(\mathbf{n}, \mathbf{n}') \rangle \mathbf{I}(\mathbf{n}') \quad \ldots\ldots\ldots\ldots (2)$$

where **I** is the intensity vector (radiance vector) of scattered light propagating in the direction **n**, ds path length element along **n** . The first term on the right-hand side of this equation describes the change of the specific intensity vector caused by extinction, whereas the second term describes the contribution of light illuminating a small volume element from all directions $\mathbf{n}'$ and scattered in the direction **n**. The radiative transfer equation must be supplemented by boundary conditions appropriate for addressing a particular physical problem.

4. COMPUTATIONAL CHARACTERIZATION TECHNIQUES FOR NONSPHERICAL PARTICLES

Different computational techniques have been developed for study of scattering by small particulate matter both spherical and non-spherical. The applicability of these methods are determined by the size of the particle relative to the wavelength of the incident radiation i.e. called size parameter. Classical methods like the finite-difference method, finite element method

or integral equation method led to computational tools that are expensive as they require higher degrees of computational resources. This significantly restricts their use in studying electromagnetic scattering by large particles. One of the method which is extensively used is null-field method for rigorous computations of electromagnetic scattering by both single and complex particulate systems significantly larger than the incident illuminating wavelength. In many applications, it is highly desirable in for thousand of particles in random orientation in complex systems and particle aggregates dispersed in both shapes and sizes in different radiative environments.

Some of these techniques are briefly explained here:

4.1. Finite Element Method (FEM)

The finite element method (abbreviated as FEM) is a numerical technique to obtain an approximate solution to a class of problems governed by elliptic partial differential equations or boundary value problems. The finite element method converts the elliptic partial differential equation into a set of algebraic equations. It computes the scattered electric field by numerically solving the vector Helmholtz equation using a set of boundary conditions at the particle surface [13, 14]. However, the disadvantage of FEM is that computations must be repeated for each new direction of incidence. So in order to simplify the scattering problem particle and orientation symmetries must be used.

The advantages of FEM are that it permits the modeling of arbitrarily shaped and inhomogeneous particles, easily executable, and avoids the

singular-kernel problem typical of the integral equation methods. However its main disadvantage is that computations are time consuming and limited to size parameters less than about 10. The finite spatial discretization and the approximate absorbing boundary condition make FEM poorly suitable to achieve numerical accuracy.

A recent modification of finite-element method can be used to simulate light scattering from arrays of high aspect-ratio nano-posts and FinFETs [15].

4.2. Finite-Difference Time-Domain method (FDTD)

The Finite-Difference Time-Domain method (FDTD) is a very popular technique for the solution of electromagnetic problems. It has been extensively used to study scattering from metal objects and dielectrics, antennas, microstrip circuits, and electromagnetic absorption in the human body exposed to radiation. The main advantage of FDTD method is that it is extremely simple, even for programming a three-dimensional code. The technique was first proposed by K. Yee [16, 17]. FDTD is based on discretizing the Maxwell's equations with central difference approximations both in time and space. It's simply implies the allocation of electric and magnetic field components in space, and then allowing a time evolution.

FDTD basically calculates electromagnetic scattering in the time domain by directly solving Maxwells time dependent curl equations [16]. The space and time derivatives of the electric and magnetic fields are approximated using a finite difference scheme with space and time discretizations selected to bound computational errors and ensuring numerical stability of the

algorithm.The scattering particle is embedded in a finite computational domain, and absorbing boundary conditions are applied to model scattering in free space [5]. In FDTD there is no need to solve a large number of linear equations, so lesser memory requirements. FDTDM is popular recently because of its simplicity and ease of implementation. It holds significant advantage over a number of other numerical codes in terms of allowed size parameter.

4.3. Discrete Dipole Approximation (DDA)

The Discrete Dipole Approximation (DDA) originally known as the coupled dipole method) developed by [18] is based on approximating the target particle into a number (*N)* of elementary polarizable units called dipoles. The resultant field exciting a dipole is a superposition of the external incident field and the fields scattered by all other neighboring dipoles considering all possible internal interactions within the particle volume. This allows one to write a system of *N* linear equations for *N* fields exciting the *N* number of dipoles. The numerical solution of this system is used to compute *N* partial fields scattered by the dipoles and, thus, the total scattered field is obtained after rigorous numerical computations. The discrete-dipole approximation (DDA) is a flexible and powerful technique for computing scattering and absorption by targets of arbitrary geometry (i.e. of any kind of irregular and complex shapes). The development of efficient algorithms and the availability of inexpensive computing power together have made DDA one of the most extensively used methods of choice for many scattering problems. DDA calculations require choices for

the locations and the polarizabilities of the point dipoles used to represent the target volume. Recent development in DDA allows solution of problems involving very large values of dipole numbers. These developments particularly use complex-conjugate gradient (CCG) methods and fast-Fourier-transform (FFT) techniques, for very fast and efficient computations. DDA can be used to compute highly accurate results for targets with dielectric constants (m) with moderate values $m \leq 2$. An user friendly portable FORTRAN implementation of the DDA, the program DDSCAT has been developed by Draine and Flatau [19] is freely available as a open source code. The use of CCG and FFT in the original algorithms permits calculations for *N* as large as 10^5 so that scattering problems with size parameter $k \leq 10$ can be studied with scientific workstations using parallel computations [20, 21]. The most important advantage of DDA is its applicability to any arbitrarily shaped, inhomogeneous, and anisotropic particles. The disadvantages of the technique are limited numerical accuracy, especially for scattering matrix elements; slow convergence of results with increasing number of dipoles *N*; and the need to repeat the entire calculation for each new incident direction(for DDA with CGM-FFT) [20, 22, 23]**.** These factors have made DDA computations time consuming, especially for particle with larger size parameters and for a large number of orientation distributions, which in turn limited the particle size parameter to relatively small values. Regardless of the drawbacks it is the best choice for calculations of scattering, matrix, cross sections and efficiencies for particles with arbitrary geometry.

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4.4. T-Matrix Method

The null-field method (also known as the extended boundary condition method, Schelkunoff equivalent current method, Eswald–Oseen extinction theorem and T-matrix method) has been developed by [24, 25] as a technique for computing electromagnetic scattering by perfectly conducting and dielectric particles especially for some standard shapes. The T- Matrix approach has been used to study a number of arbitrary geometries from multilayered and composite particles to chiral particles [26, 27]. It's been also used in study of multiple scattering in a random media [28]. And it's numerical stability has been vastly improved in computations for particles with extreme geometries [29]. Several computer programs has been developed for averaging scattering characteristics over particle orientations and at the same time to compute electromagnetic scattering by axisymmetric particles in fixed and random orientations have been designed.

The particles that can be treated with T-Matrix are as follows- Homogeneous, dielectric (isotropic, uniaxial anisotropic, chiral), and perfectly conducting particles with axisymmetric and nonaxisymmetric surfaces, Inhomogeneous, layered and composite particles,, Clusters of arbitrarily shaped particles, and Particles on or near a plane surface. The null-field method is used to compute the T matrix of each individual particle and the T-matrix formalism is employed to analyze systems of particles. There is a number available FORTRAN code in public domain and the Internet available computer programs developed by [30, 31]. For specific applications, other computer codes have been developed by various

research groups, but these programs are currently not publicly available as open source codes. The T -matrix method (TMM) is based on expanding the incident field in Vector Spherical Wavefunctions (VSWF) regular at the origin and expanding the scattered field outside a circumscribing sphere of the scatterer in VSWFs regular at infinity. The *T* matrix transforms the expansion coefficients of the incident field into those of the scattered field and, if known, can be used to compute any scattering characteristic of a nonspherical particle [6].

T- Matrix can be applied to any particle shape, although TMM computations are much simpler and more efficient for rotationally symmetric particles. Almost all existing computer codes assume rotationally symmetric shapes both smooth, for example, spheroids and so-called Chebyshev particles, and sharp edged, for example, finite circular cylinders [32]. The loss of efficiency for particles with large aspect ratios or shapes without axial symmetry is the main disadvantage of TMM. The advantage is that it is highly accurate, fast and applicable to particles with equivalent sphere size parameters exceeding 100 [33]. The elements of the *T* matrix are independent of the incident and scattered fields and depend only on the shape, size parameter, and refractive index of the scattering particle and on its orientation with respect to the reference frame, so that the *T* matrix need be computed only once and then can be used in computations for any directions of incident and scattered light waves. Recent developments including an analytical orientation-averaging approach that makes computations for randomly oriented, rotationally symmetric particles as fast as those for a particle in a fixed orientation and later also extended to

arbitrary clusters of spheres. Another analytical procedure was developed for computing the extinction matrix for nonspherical particles axially oriented by magnetic, electric, or aerodynamic forces [34, 35].

4.5. Geometric Optics Approximation (GOA)

The geometric optics approximation (GOA) (otherwise known as the ray tracing or ray optics approximation) is a universal approximate method for computing light scattering by particles much larger than wavelength of the incident electromagnetic wave. GOA is based on the assumption that the incident plane wave can be represented as a collection of independent parallel rays. The history of each ray impinging on the particle surface is traced using the Snell law and Fresnel's equations. The sampling of all escaping light rays into predefined narrow angular bins supplemented by the computation of Fraunhofer diffraction of the incident wave on the particle projection yields a quantitative representation of the particle scattering properties. GOA is particularly simple for spheres because the ray paths remain in a plane. For other particles, ray tracing is usually performed using a Monte Carlo approach [36, 37]. The main advantage of GOA is that it can be applied to essentially any arbitrary shape. However, GOA is always an approximate method, and its range of applicability in terms of the smallest size parameter should be checked by comparing GOA results with exact numerical solutions of Maxwell's equations.

The very existence and use of many numerical techniques for computing electromagnetic scattering by nonspherical particles indicate that there is no single technique that provides the best results in all cases for any shape and

orientations. Depending on a particular application each approach may prove to be more appropriate in terms of efficiency, accuracy, and applicability to the particle physical parameters. Furthermore, it is very difficult to develop and apply simple and objective criteria in order to examine the relative performance of different numerical techniques which already find its way in a wide range of applications. The availability of a well-documented public-domain computer code is also an important factor to take into account other than Mie theory we can consider DDA and T-Matrix in this case. Benchmark results for spheroids, finite circular cylinders, Chebyshev particles, and two-sphere clusters in fixed and random orientations were reported a number of times [38, 39]. All these available techniques are simple in concept and software implementation and seem to have commendable performance characteristics. But the simplicity and flexibility of these techniques are often accompanied by a substantial loss in efficiency and accuracy and by stronger practical limitations on the maximal particle size parameter. Further work is obviously required in order to develop a method that is efficient, flexible, and applicable to a wide range of size parameters.

5. OPEN SOURCE COMPUTATIONAL CODES

Some of the most popular and widely used codes available in the public domain are:

5.1. T -matrix Program

A FORTRAN computer program has been written to solve various scattering problems in the framework of the null-field method. Essentially,

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the basic principle of the code is that it performs a convergence test and computes the T-matrix and the scattering characteristics of particles with uniform orientation distribution functions. An important part of the T - matrix calculation is the convergence procedure over the maximum expansion order N_{rank}, maximum azimuthal order M_{rank} and the number of integration points N_{int}. In fact, these are the input parameters and their optimal values must be specified by the user. This is accomplished by repeated convergence tests based on the analysis of the differential scattering cross-section [5]. The scattering characteristics depend on the type of the orientation distribution function. By convention, the uniform distribution function is called complete if the Euler angles α, β and γ are uniformly distributed in the intervals (0 to 360°), (0 to 180°) and (0 to 360°), respectively. The normalization constant is 4π for axisymmetric particles and $8\pi^2$ for nonaxisymmetric particles. The input parameters for this code are particle radius, real part of particle refractive index, imaginary part of particle refractive index, real part of medium refractive index and incident wavelength, or simply size parameter for calculations for a single particle. The output parameters are scattering angle (θ) and all non zero elements of the scattering matrix. The size paramater (x), scattering efficiency (Q_{sca}), extinction efficiency (Q_{ext}), backscattering efficiency (Q_{back}), absorption efficiency (Q_{abs}), radiation pressure (Q_{pr}), single scattering albedo and asymmetry parameter (g).

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5.2. DDSCAT Program

DDSCAT 7.3 is a freely available open-source Fortran-90 software package applying the "discrete dipole approximation" (DDA) to calculate scattering and absorption of electromagnetic waves by targets with arbitrary geometries and complex refractive index. The targets may be isolated entities (e.g., dust particles), but may also be 1-d or 2-d periodic arrays of "target unit cells", which can be used to study absorption, scattering, and electric fields around arrays of nanostructures. DDSCAT allows accurate calculations of electromagnetic scattering from targets with size parameters $2\pi a_{eff} / \lambda \leq 25$ provided the refractive index m is not large compared to unity $(|m-1| \leq 2)$. DDSCAT includes support for MPI, OpenMP, and the IntelR Math Kernel Library (MKL). DDSCAT supports calculations for a variety of target geometries (e.g., ellipsoids, regular tetrahedra, rectangular solids, finite cylinders, hexagonal prisms, etc.). Target materials may be both inhomogeneous and anisotropic. It is straightforward for the user to "import" arbitrary target geometries into the code. DDSCAT automatically calculates total cross sections for absorption and scattering and elements of the Scattering intensity matrix for specified orientation of the target relative to the incident wave, and for specified scattering directions. DDSCAT 7.3 can calculate scattering and absorption by targets that are periodic in one or two dimensions. DDSCAT can calculate and store electric and magnetic values E and B throughout a user-specified rectangular volume containing the target. A Fortran-90 code ddapostprocess to support postprocessing of P, and nearfield E and B, is included in the software package. DDSCAT is

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intended to be a versatile tool, suitable for a wide variety of applications including studies of interstellar dust, atmospheric aerosols, blood cells, marine microorganisms, and nanostructure arrays. The principal advantage of DDA is that it is completely flexible regarding the geometry of the target, being limited only by the need to use an interdipole separation (d) small compared to (1) any structural lengths in the target, and (2) the wavelength. The second criterion is adequately satisfied if;

$$|m|kd < 1 \quad \text{..... (3)}$$

where m is the complex refractive index of the target material, and $k \equiv 2\pi/\lambda$, where λ is the wavelength in vacuum. This criterion is valid provided $|m-1| \leq 3$ or so. When imaginary part of m becomes large, the DDA solution tends to overestimate the absorption cross section C_{abs}, and it may be necessary to use interdipole separations d smaller than indicated by eq. (1). If accurate calculations of the scattering phase function (e.g., radar or lidar cross sections) are desired, a more conservative condition $|m|kd < 0.5$. Let V be the actual volume of solid material in the target. If the target is represented by an array of N dipoles, located on a cubic lattice with lattice spacing d, then $V = Nd^3$. We characterize the size of the target by the "effective radius" $a_{eff} \equiv (3V/4\pi)^{1/3}$ the radius of an equal volume sphere. A given scattering problem is then characterized by the dimensionless "size parameter"

$$x \equiv ka_{eff} = 2\pi a_{eff}/\lambda \quad \text{…….(4)}$$

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Practical considerations of CPU speed and computer memory currently available on scientific workstations typically limit the number of dipoles employed to $N < 10^6$ (limitations on N arise due to available RAM). It is therefore clear that the DDA is not suitable for very large values of the size parameter x, or very large values of the refractive index m. The primary utility of the DDA is for scattering by dielectric targets with sizes comparable to the wavelength [19, 20].

DDA mainly calculates:

1. Absorption and Scattering by Finite Targets.
2. Absorption and Scattering by Periodic Arrays of Finite Structures.
3. Application to Targets in Dielectric Media.

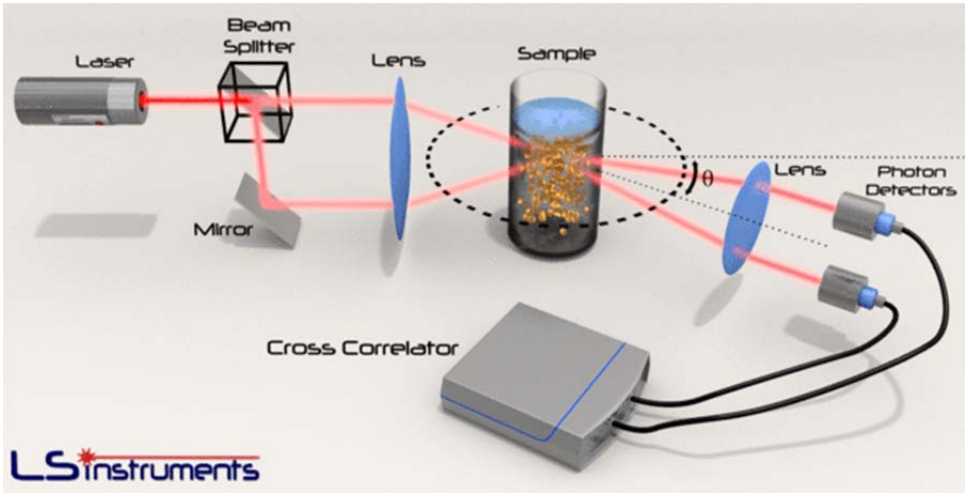

Fig. 5: A typical Light scattering set up. (Image source: LS instruments, [http://www.lsinstruments.ch/])

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6. LIGHT SCATTERING EXPERIMENTATIONS

Existing measurements of electromagnetic scattering by nonspherical particles are constrained by the state of source and detector technology and the lack of windows in the spectrum of Earth's atmosphere, and traditionally fall into two categories:

1. Scattering of visible and infrared light by particles with sizes ranging from a few nanometers to several hundred micrometers.

2. Microwave scattering by millimeter- and centimeter-sized objects. Visible and infrared measurements involve relatively simpler, cheaper, and more portable instrumentation and can be performed in the field as well as in the laboratory. Microwave experiments, by contrast, require expensive instrumentations.

In a typical light scattering experimental setup for measuring the full scattering matrix using visible or infrared light, the beam produced by a light source (usually a laser) passes a linear polarizer and a polarization modulator and then illuminates particles contained in a jet stream or a scattering chamber. Light scattered by the particles at an angle passes a through a quarter-wave plate (optionally) and a polarization analyzer before its intensity is measured by a detector. It is assumed that the scattering plane acts as the plane of reference for defining the Stokes parameters. The Mueller matrices of the polarizer, modulator, quarterwave plate, and analyzer depend on their orientation with respect to the scattering plane and can be precisely varied. Several measurements with different orientations of the optical components with respect to the scattering plane are required for the full determination of the scattering matrix. But Visible and infrared

measurements often suffer from the inability to accurately characterize the size and shape of scattering particles. Another serious problem is that the arrangement of the light source and the detector usually avoids measurements at scattering angles close to 0° and 180° because the intense laser light may destroy the detector at those extreme angles [5, 9]. Extinction cross-sectional measurements have traditionally suffered from the problem that a detector with a finite aperture picks up some of the light scattered by particles in the forward direction. Early scattering experiments used unpolarized incident light and were limited to measurements of the scattered intensity and the degree of linear polarization. Despite the availability of advanced experimental techniques, the number of measurements of the complete scattering matrix remains relatively small due to the complexities of using a number of combinations of analyzer and polarizers to get the scattering parameters.

7. CONCLUSIONS AND FUTRUE SCOPES OF NON-SPHERICITY STUDIES IN LIGHT SCATTERING

The most important reason for modeling polydisperse samples both in size and shape rather than monodisperse, is that computations and measurements of light scattering will be more realistic considering the natural particle systems are often distributed over a range of size, shapes and orientations. The second reason is the presence of the complicated and highly variable interference structure for monodisperse particles in a fixed orientation, which makes it essentially impossible to use computations for monodisperse particles in order to derive useful conclusions about the effect of

nonsphericity on light scattering. Studies shows that averaging over sizes for spheres and averaging over orientations and sizes for nonspherical particles largely removes the typical interference structures in scattering patterns and enables meaningful comparisons of the scattering properties of realistic particles with theoretical models. All characteristics of light scattering substantially depend on the morphology, constituent material, and size of particles. It is very important to perform accurate modeling, computations and numerical simulations of irregularly shaped particles for realistic and highly effcicient interpretationse of natural particles, atmospheric aerosols, terrestrial and interstellar dust, nanoparticle systems which are highly irregular and complex in morphology. It is desirable to develop more advanced and refined algorithms to compute the optical and physical properties of non-spherical particles applicable in light scattering studies of small particulate matter.

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